

Acoustic Monitoring of Night-Migrating Birds: A Progress Report

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Abstract—This paper discusses an emerging methodology that uses electronic technology to monitor vocalizations of night-migrating birds. On a good migration night in eastern North America, thousands of call notes may be recorded from a single ground-based, audio-recording station, and an array of recording stations across a region may serve as a “recording net” to monitor a broad front of migration. Data from pilot studies in Florida, Texas, New York, and British Columbia illustrate the potential of this technique to gather information that cannot be gathered by more conventional methods, such as mist-netting or diurnal counts. For example, the Texas station detected a major migration of grassland sparrows, and a station in British Columbia detected hundreds of Swainson’s Thrushes; both phenomena were not detected with ground monitoring efforts. Night-flight calls of 35 species of migrant landbirds have been identified by spectrographic matching with diurnal calls recorded from known-identity individuals; call types of another 31 species are known, but are not yet distinguishable from other similar calls in several species complexes. Efforts to use signal-processing technology to automate the recording, detection, and identification of night-flight calls are currently under way at the Cornell Lab of Ornithology. Automated monitoring of night-flight calls will soon provide information on migration routes, timing, and relative migration density for many species of birds. Such information has application for conservation planning and management, as well as for assessing population trends.

Most species of North America’s migrant landbirds make their transcontinental flights at night, and many species give short vocalizations while they fly. By aiming microphones at the night sky, a volume of sky—with dimensions dependent on microphone design—can be monitored for calls (Graber and Cochran 1959). A variety of microphone and recording station designs have been used for this purpose, depending on the specific monitoring goals and the recording environment (Graber and Cochran 1959; Dierschke 1989; Evans 1994). In many regions of North America, a recording station may detect thousands of calls during a single migration night (Graber and Cochran 1960; Evans 1994). Species known to give night-flight calls include the warblers (*Parulinae*), sparrows (*Emberizinae*), cuckoos (*Cuculidae*), rails (*Rallidae*), herons (*Ardeidae*), and Catharus thrushes. Groups not known

to give regular vocalizations in night migration are the vireos (*Vireonidae*), flycatchers (*Tyrannidae*), and orioles (*Icterinae*). If a monitoring protocol is consistently maintained, an array of microphone stations can provide information on how the species composition and number of vocal migrants vary across time and space. Such data have application for monitoring avian populations and identifying their migration routes. In addition, detection and classification of distinctive call-types is possible with computers (Mills 1995; Taylor 1995), thus information on bird populations might be gained automatically. In this paper, we summarize the current state of knowledge for identifying night-flight calls to species; present selected results from four ongoing studies that are monitoring night-flight calls; and discuss the implications of this research for conservation of migratory landbirds.

Methods

Field Recording

Pressure Zone Microphones (PZMs) designed by Evans were used in conjunction with high-fidelity video cassette recorders (hi-fi VCRs) to enable directional sound pickup and inexpensive recording of avian night-flight calls over long periods. The microphones were designed to be especially sensitive in the two-to-nine kilohertz range, and to reject land-born environmental noise. Hi-fi VCRs allowed 8-10 hours of continuous 2-channel recording of sound from the night sky, and could be programmed for regular nightly operation. Recording sites were chosen in areas relatively free of vegetation to minimize wind and insect noise; several microphones were operated in open fields that were relatively free of insect song. Most sites included a building with A. C. power on which microphones could be positioned to provide unobstructed access to the sky, and someone living either at the site or close enough to assist in operating the recording equipment by changing tapes once per day.

From 1991 through 1994, a line of stereo recording stations was operated across central New York State during fall migration (fig. 1). Four sites were operated in 1991 (A, B, I, and O); five sites were operated in 1992 (A, B, M, I, and O); seven sites in 1993 (C, A, B, I, R, O, and J) and seven in 1994 (C, A, B, I, R, N, O). Six of these sites were located at residences (C, A, M, R, N, and J), two on old barns (B and O), and one was operated by battery in a short-grass field (I). In addition, recording stations were operated in southern Texas at Laguna Atascosa National Wildlife Refuge during the spring migrations of 1994-1996, at the southern end of Vancouver Island in British Columbia during spring and fall of 1995, and in eastern Florida during the springs of 1989, 1991,

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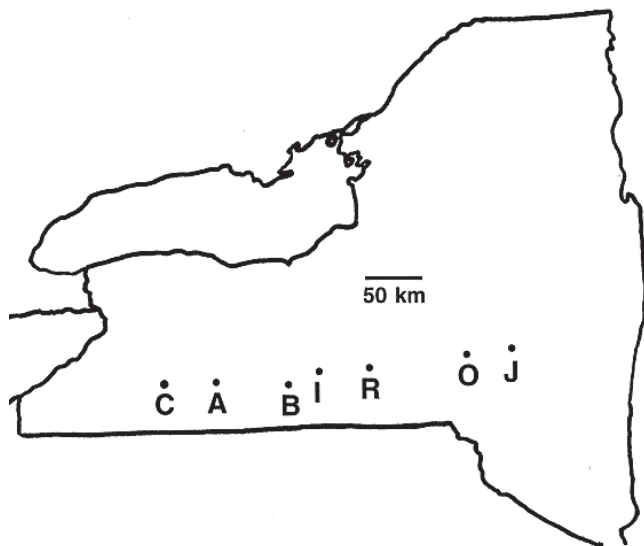


Figure 1—Location of night-flight call recording stations across New York State. Letters are from the closest town to each recording station. C = Cuba; A = Alfred; B = Beaver Dams; I = Ithaca; R = Richford; O = Oneonta; J = Jefferson.

1993, 1995, and 1996. Recordings were made either every night or when weather conditions were conducive to migration. At the sites in New York State, microphones were positioned 0.6 meters apart on an east-to-west line, with the east microphone angled 20 degrees from vertical toward the southeast, and the west microphone angled 20 degrees from the vertical toward the southwest. This positioning helped to dispel rainwater and shielded the microphones from direct buffeting by northerly winds.

The sensitivity pattern of a microphone design was determined using a ground-based eight-channel microphone array (Evans and others, in preparation). Eight microphones were laid out within a 75 meter by 75 meter area, four at the corners of the area and four at the corners of a 30 meter by 30 meter square centered in the interior of the larger square. This layout enabled calls from birds flying in the vicinity of the array to be picked up by all eight microphones. It also allowed the approximate point of origin of a night-flight call to be determined by analyzing its varying arrival times at the different microphones. By plotting such locations for hundreds of night-flight calls, the shape of a microphone's detection pattern and its range of detection for different species became evident. The detection range is defined here as the distance within which a call can be detected by the microphone and still be identified to species by spectrographic analysis or by ear. This range varies due to differing call loudness among species, the distinctiveness of their acoustic signatures, and variables in the recording environment.

The eight channel study revealed that the microphone design used in New York State, Texas, and part of the Florida study had a maximum above-ground detection range of 300 meters for a wide range of warblers and sparrows. Furthermore, the maximum horizontal cross-section of sky

that a single microphone had for detecting such calls was approximately 250 meters. The calls of *Catharus* thrushes, which are louder than warbler and sparrow calls, were detectable to 600 meters above a recording site, and a single microphone covered an approximate 1,000 meter cross-section of sky; the stereo setup covered an approximate 1,500 meter cross-section.

Call Detection and Analysis

Calls were detected on the recordings by listening through headphones (Evans) and by signal analysis software written in the Bioacoustics Research Program at the Cornell Laboratory of Ornithology (Mills 1995). This software was designed to detect short high-pitched call notes, which range in frequency from 5-9 kHz. All sound analysis employed the software program Canary (Charif and others 1995). Spectrographs of calls presented in this paper were made from calls digitized with a 22254 Hz sampling rate and processed using a 256 point FFT, 128 point frame size, 87.5% overlap, and Hanning window (frequency resolution 86 Hz, time resolution 0.72 msec, analysis bandwidth 700 Hz).

Recordings were analyzed by interpreting bird call sequences to derive a minimum number of individuals passing (MIP). The MIP technique is based on human interpretation of the sequences of bird calls on audio recordings. The human listener considers time delays between calls, amplitude differences between calls, stereo location of calls, and expected bird flight speeds in conjunction with the pickup pattern of the microphone(s), to interpret a minimum number of individuals passing over (Evans and Mellinger 1999).

In this paper, for MIP analysis on warbler night-flight calls from Florida, we assumed that calls from the same species (or species complex) occurring within one minute of each other were from the same individual. Calls occurring more than one minute apart were interpreted to be from different individuals. This formula is based on an estimated minimum bird flight speed of 20 km/hour (330 meters per minute) and a maximum horizontal pickup pattern of 250 meters. Note that our estimates of the number of calling individuals are probably low, because most birds probably pass through the pickup zone in less than one minute, and because two individuals could call within one minute.

Based on similar calculations, our MIP analysis of thrushes assumed that calls more than two minutes apart were from different individuals, and both stereo analysis of time delays and amplitude differences were used to discriminate individuals within two minute periods. Thrush calls are louder than warbler and sparrow calls, so they can be heard over a larger region of sky.

Identification of Nocturnal Flight Calls

A long-standing impediment to the development of night-flight call monitoring has been call identification. The night-flight calls of many species, such as warblers and sparrows, are like single cricket chirps, typically between 0.05 and 0.25 seconds long. Their high frequencies (5-9 kHz) make them especially difficult for the human ear to distinguish.

Since 1985, Evans has systematically determined the type of night-flight call given by most species in eastern

North America. Three techniques were used to acquire this information (see Evans 1994). First, structural details of night-flight calls were compared with diurnal calls of known identity through spectrographic analysis (fig. 2). The diurnal calls were typically recorded from birds in visible flight, and such calls were considered as likely to be the same call type used during night migration. The other two methods of call determination consisted of correlating the seasonal timing and geographic range in which various types of night-flight calls were recorded with known timing and migration ranges for each species.

All identifications of recorded night-flight calls used in the analyses described here were performed by aural comparison, or by visual comparison of spectrographs, to diurnal calls of verified identity for each species.

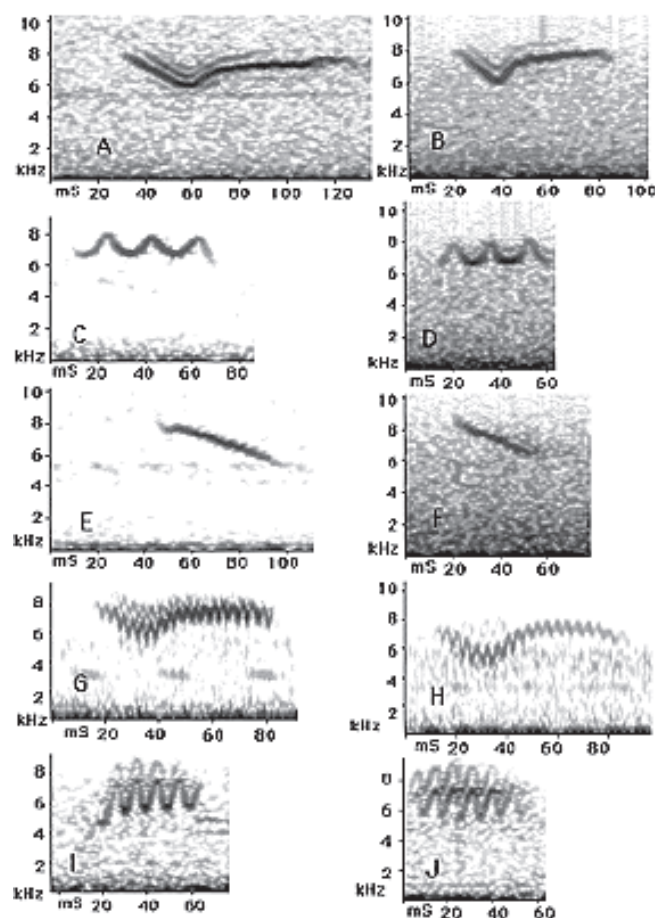


Figure 2—Identification of nocturnal flight calls through spectrographic comparison with diurnal calls for selected species migrating along the east coast of Florida. A = Presumed night-flight call of American Redstart; B = Diurnal flight note of American Redstart; C = Night-flight call of species complex #5; D = Diurnal flight note of Blackpoll Warbler; E = Night-flight call of species complex #4; F = Diurnal flight note of Parula Warbler; G = Presumed night-flight call of a Black-and-White Warbler; H = Diurnal flight note of a Black-and-White Warbler; I = Presumed night-flight call of a Common Yellowthroat; J = Diurnal flight note of a Common Yellowthroat.

Results

The night-flight calls of 35 migrant landbird species in eastern North America are now known to be distinguishable either by ear or by spectrographic analysis (table 1), and evidence exists for the type of call given by 31 additional migrant species (W. Evans and M. O'Brien, unpublished data). The calls of these latter species are not yet distinguishable from one or more other species with similar call-types (table 2). In addition, many species of shorebirds and waterfowl, as well as herons, bitterns, gulls, terns, and rails, give vocalizations at night that may be recognized by their similarity to the birds' typical diurnal calls.

Following are selected results from four pilot studies in North America where night-flight call monitoring has been in operation. These results illustrate the progress being made in the areas of species identification, counting techniques, comparisons with ground-based surveys, and the biology of nocturnal migration.

Species Identification and Counting: Caribbean Migrants in Florida

To begin the complex process of sorting out species identifications and counting techniques, we initially searched for a geographic region that was relatively well-known, in terms of bird migration, and where nocturnal migration was limited to relatively few common species. We found such a region on the east coast of Florida. An outstanding historical database exists for east-central Florida, due to compilations by Cruickshank (1980) and Taylor (1976). This includes 25 years of visual migration observations and extensive information from tower-kills, both of which define migration periods and relative abundance patterns for many species of migrants. The data show that the majority of passerine migrants during spring in eastern Florida are species known to winter in the Caribbean Islands or which fly over the Caribbean enroute from South American wintering grounds. Such species include Common Yellowthroat (*Geothlypis trichas*), Ovenbird (*Seiurus aurocapillus*), Blackpoll Warbler (*Dendroica striata*), American Redstart (*Setophaga ruticilla*), Cape May Warbler (*Dendroica tigrina*), Black-throated Blue Warbler (*Dendroica caerulescens*), Black-and-white Warbler (*Mniotilta varia*), Northern Parula (*Parula americana*), Northern Waterthrush (*Seiurus Novaboracensis*), Connecticut Warbler (*Oporornis agilis*), Bobolink (*Dolichonyx oryzivorus*), and Bicknell's Thrush (*Catharus bicknelli*). Because of these well-known migration patterns and the relatively simple species composition, we established a recording station on the east coast of Florida to determine the night-flight call identities of these Neotropical migrant species.

During five spring migrations, this recording station recorded over 50,000 calls of migrating birds. Basic evidence for the identity of these species' night-flight calls was compiled by spectrographically matching migratory contact notes from observed birds during the day with distinctive night-flight calls (fig. 2). Identities were then further corroborated by matching the seasonal time of occurrence of the tentatively identified call-types with the migrational databases compiled by Cruickshank and Taylor (Evans, in

Table 1—Migratory landbird species in eastern North America with known nocturnal flight calls distinguishable by ear or by spectrographic analysis. Note that calls of other species are known, but are not yet distinguishable from similar species (see table 2).

Species	Vocalization
Upland Sandpiper (<i>Bartramia longicauda</i>)	rapid “tu tu tup” series (variable)
Long-billed Curlew (<i>Numenius americanus</i>)	Cur-lee flight call
Black-billed Cuckoo (<i>Coccyzus erythrophthalmus</i>)	guttural “chuckle”
Yellow-billed Cuckoo (<i>Coccyzus americanus</i>)	kakakowlp call (variable)
Red-headed Woodpecker (<i>Melanerpes erythrocephalus</i>)	“queeer” note
Red-breasted Nuthatch (<i>Sitta canadensis</i>)	“aah, aah, aah” notes
Veery (<i>Catharus fuscescens</i>)	short whistled note
Gray-cheeked Thrush (<i>Catharus minimus</i>)	short whistled note
Bicknell’s Thrush (<i>Catharus bicknelli</i>)	short whistled note
Swainson’s Thrush (<i>Catharus ustulatus</i>)	short whistled note
Hermit Thrush (<i>Catharus guttatus</i>)	short whistled note
Wood Thrush (<i>Hylocichla mustelina</i>)	shortwhistled note
Chestnut-sided Warbler (<i>Dendroica pensylvanica</i>)	short, high “tseep”
Cape May Warbler (<i>Dendroica tigrina</i>)	short, high “tseep”
Black-throated Blue Warbler (<i>Dendroica caerulescens</i>)	short, high “tseep” (often doubled)
Palm Warbler (<i>Dendroica palmarum</i>)	short, high “tseep”
Black-and-white warbler (<i>Mniotilta varia</i>)	short, high “tseep”
American Redstart (<i>Setophaga ruticilla</i>)	short, high “tseep”
Ovenbird (<i>Seiurus aurocapillus</i>)	short, high “tseep”
Northern Waterthrush (<i>Seiurus noveboracensis</i>)	short, high “tseep”
Common Yellowthroat (<i>Geothlypis trichas</i>)	short, buzzy “tzzp”
Canada Warbler (<i>Wilsonia canadensis</i>)	short, high “tseep”
Rose-breasted Grosbeak (<i>Pheucticus ludovicianus</i>)	short whistled note
Dickcissel (<i>Spiza americana</i>)	buzzy flight note
Indigo Bunting (<i>Passerina cyanea</i>)	buzzy flight note
Painted Bunting (<i>Passerina ciris</i>)	buzzy flight note
Blue Grosbeak (<i>Guiraca caerulea</i>)	buzzy flight note
American Tree Sparrow (<i>Spizella arborea</i>)	short, high “tseep”
Chipping Sparrow (<i>Spizella passerina</i>)	short, high “tseep”
Savannah Sparrow (<i>Passerculus sandwichensis</i>)	short, high “tseep”
Grasshopper Sparrow (<i>Ammodramus savannarum</i>)	short, high “tseep”
Henslow’s Sparrow (<i>Ammodramus henslowii</i>)	a high descending “zeee”
Lincoln’s Sparrow (<i>Melospiza lincolni</i>)	a buzzy “zee”
Swamp Sparrow (<i>Melospiza georgiana</i>)	a buzzy “zee”
Bobolink (<i>Dolichonyx orizivorus</i>)	pink flight note

preparation). One important discovery was the probable night-flight call of Bicknell’s Thrush (Evans 1994), a high-priority species for monitoring along the Atlantic Coast.

A 15 minute sample of analyzed one channel audio data from this Florida station shows the temporal occurrence of calls from different species and species complexes (fig. 3). Analysis of this calling sequence using the MIP method revealed that a minimum of seven Ovenbirds, seven individuals in the species complex #5 (table 2), two individuals in species complex #4, two Common Yellowthroats, and two American Redstarts passed over the recording station during the 15 minute period. In addition, detection of single calls from a Black-throated Blue Warbler, Northern Waterthrush, and Black-and-white Warbler during the 15 minute period were interpreted as evidence for the passage of at least one individual of each of these species. On this evening, winds were southwesterly at 10-20 km/hr and the sky was clear. Given these conditions, birds were assumed to be heading northward and not circling.

Comparisons With Ground-Based Banding and Surveys

In 1994, a nocturnal flight call monitoring station was established at Laguna Atascosa National Wildlife Refuge (LANWR) in south Texas. The study was conducted in part to supplement information on migration gathered from a United States Fish and Wildlife Service (USFWS) banding operation at the refuge. Data from this study are still being analyzed, but early results have revealed valuable information.

The most common passerines detected acoustically were very different from the most common species detected by mist-netting. For example, the banding data included large numbers of White-eyed Vireos (*Vireo griseus*) and Yellow-breasted Chats (*Icteria virens*), two species that are not known to give calls in night migration. At the same time, the acoustic technique revealed large flights of Savannah Sparrows (*Passerculus sandwichensis*), Grasshopper Sparrows

Table 2—“Complexes” of bird species for which call-type is known but which are not yet definitely distinguishable from other species with similar call-types. All these calls are short, typically less than 1/10th of a second in duration and high pitched, between 5 and 9 kHz.

Species complex	Vocalization
I Prothonotary Warbler (<i>Protonotaria citrea</i>) Clay-colored Sparrow (<i>Spizella passerina</i>) Swainson's Warbler (<i>Limnothlypis swainsonii</i>)	A nonsibilant, rising “tseep” note
II Blue-winged Warbler (<i>Vermivora pinus</i>) Golden-winged Warbler (<i>Vermivora chrysoptera</i>) Louisiana Waterthrush (<i>Seiurus motacilla</i>)	A buzzy “kzeen” of “kzeep” note
III Tennessee Warbler (<i>Vermivora peregrina</i>) Nashville Warbler (<i>Vermivora ruficapilla</i>) Orange-crowned Warbler (<i>Vermivora celata</i>) Black-throated Green Warbler (<i>Dendroica virens</i>) Vesper Sparrow (<i>Pooecetes gramineus</i>) Yellow-rumped Warbler (<i>Dendroica coronata</i>) White-crowned Sparrow (<i>Zonotrichia leucophrys</i>)	A sibilant, rising “tseet” or “tsee” note
IV Pine Warbler (<i>Dendroica pinus</i>) Northern Parula (<i>Parula americana</i>) Field Sparrow (<i>Spizella pusilla</i>) Yellow-throated Warbler (<i>Dendroica dominica</i>) Prairie Warbler (<i>Dendroica discolor</i>)	A descending “tsew” note
V Cerulean Warbler (<i>Dendroica cerulea</i>) Blackburnian Warbler (<i>Dendroica fusca</i>) Magnolia Warbler (<i>Dendroica magnolia</i>) Worm-eating Warbler (<i>Helmitheros vermivorus</i>) Blackpoll Warbler (<i>Dendroica striata</i>) Yellow Warbler (<i>Dendroica petechia</i>) Bay-breasted Warbler (<i>Dendroica castanea</i>) Connecticut Warbler (<i>Oporornis agilis</i>)	A buzzy, “zeet” note
VI Fox Sparrow (<i>Passerella iliaca</i>) Song Sparrow (<i>Melospiza melodia</i>) White-throated Sparrow (<i>Zonotrichia leucophrys</i>)	A high, “tseep” note
VII LeConte's Sparrow (<i>Ammospiza leconteii</i>) Sharp-tailed Sparrow (<i>Ammospiza ssp.</i>)	A high downslurred “tsee” note

(*Ammodramus savannarum*), and Dickcissel (*Spiza americana*) whereas none of these species were netted (Evans and Mellinger 1999).

An exciting finding from the acoustic station at LANWR was the detection of Black Rails (*Laterallus jamaicensis*) in night migration from mid-April through early May 1994. Black Rails are not known to breed or winter in southernmost Texas, so detection of their night-flight calls at LANWR suggests that the species may still be a Neotropical migrant wintering somewhere along the east coast of Mexico.

A second comparison between acoustic monitoring and ground-based data comes from New York State. In this case, a comparison is made between nocturnal flight call data for another commonly detected migrant, the Gray-cheeked Thrush, with data from two banding stations in west-central

New York. One banding station, operated by Elizabeth Brooks near Alfred, NY, was located approximately 1 mi. from the acoustic station at Alfred (station A; fig. 1). The other banding station was at the Braddock Bay Bird Observatory, located approximately 60 miles north of station A. During the fall migrations of 1990-1994, the banding station at Alfred netted an average of <1 Gray-cheeked Thrush per year, while from 1986-1995, the station at Braddock Bay averaged 22 per season (ranging from 7 to 53 per year). In 1991, 1992, 1994, and 1995, the acoustic station at Alfred detected 206, 210, 220, and 139, respectively. (Due to equipment failure, the last week of September 1995 was missed; a likely reason for the lower total). Of further interest is the consistent seasonal timing of Gray-cheeked Thrush passage revealed by the acoustic data (fig. 4). Peak passage occurred

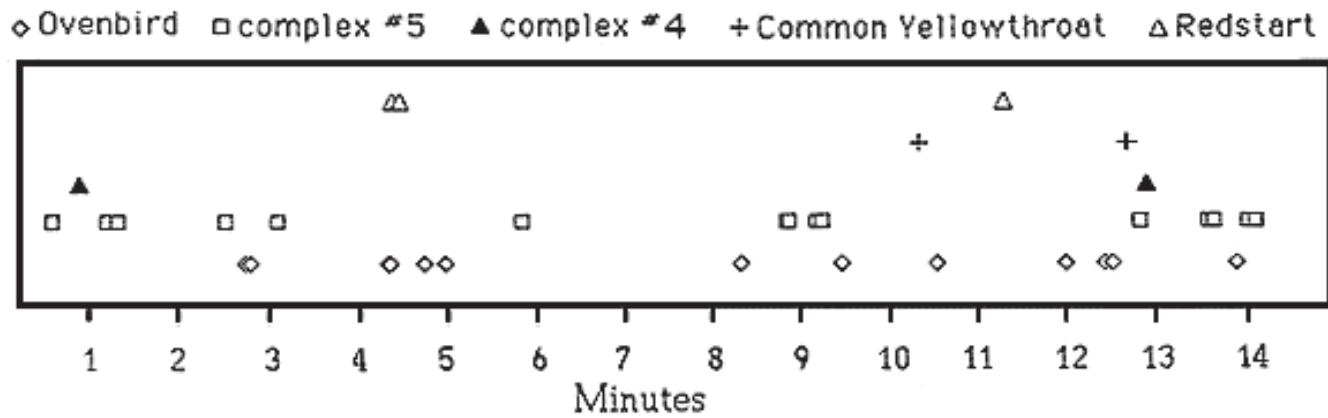


Figure 3—Example of the minimum individuals passing (MIP) technique applied to five warbler species in a 15 minute sequence from one audio channel, recorded 7 May 1989 on the east coast of central Florida. See text for discussion of MIP.

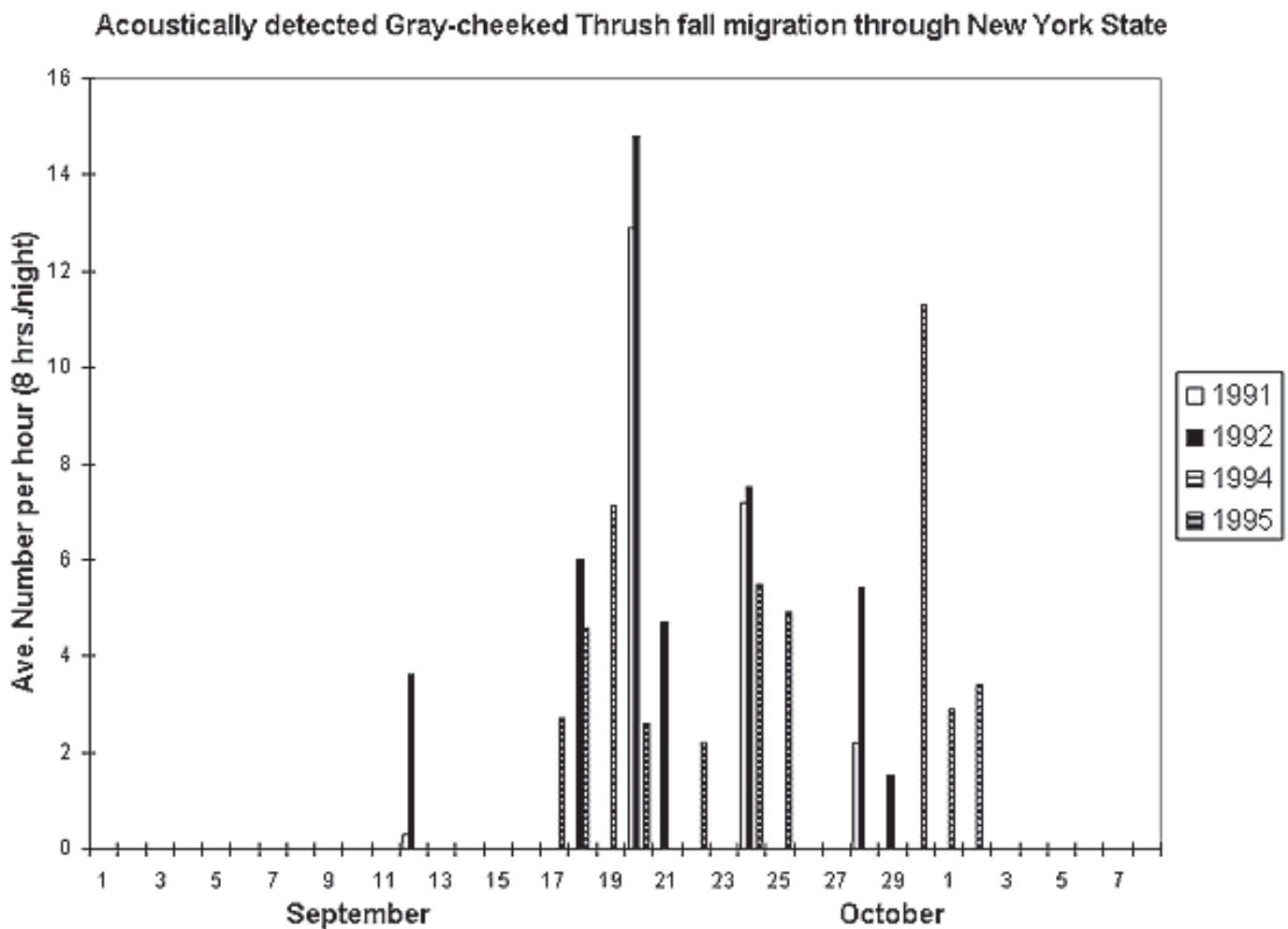


Figure 4—Average number of Gray-cheeked Thrushes per hour (8 hours of monitoring per night) detected at acoustic stations A and B during the fall migrations of 1991, 1992, 1994, and 1995.

each year during a 2-week period from 17 September to 2 October, and the bulk of their migration occurred on only 4 to 6 nights each season.

A third comparison between acoustic monitoring and ground-based data comes from British Columbia, where nocturnal-flight call monitoring was incorporated into a nongame avian-monitoring program by Rhonda Millikin of the Canadian Wildlife Service (CWS). In addition to acoustic monitoring, the program used mist-netting, transects, estimated totals, and radar with a goal to monitor species composition and density of avian migration across British Columbia. A primary focus of this research is to determine locations of migratory funnel points for establishing long-term monitoring stations.

Identities of night-flight calls of migrant passerines in western North America are not well known. However, calls of species such as Swainson's Thrush are similar to their calls in eastern North America. Acoustic monitoring in BC during fall 1995 revealed results similar to those from NY, regarding the number of individuals monitored by a single recording station compared with mist net data. During four migration nights when the acoustic technique was used, 495 Swainson's Thrushes were detected using the MIP technique, whereas only 20 Swainson's Thrushes were mist-netted during the entire fall migration period. The mist net operation involved 10-15 nets running for six hours a day in riparian habitat.

Documenting Broad-Front and Other Migration Patterns

The potential of the acoustic technique for detecting large numbers of individuals is even more promising when an array of recording stations is used. Since 1991, experiments with an array of stations across New York State have uncovered many interesting aspects of avian night migration. Foremost is the revelation of broad-front density correlations in night migration; i.e., the density of calling individuals of certain species shows similar temporal patterns (seasonal and within-night) across broad geographic areas (Evans and Mellinger 1999). These patterns are illustrated for the Veery (*Catharus fuscescens*) on a typical fall migration night in upstate New York (fig. 5). Note the similar hourly pattern of Veery passage within two pairs of stations, both about 40 km apart (fig. 1).

Based on the estimated 1,500 meter cross-section of sky that each stereo microphone station censuses for *Catharus* thrushes, interpolation of the Veery passage across New York State on the night of 28-29 August 1993 (fig. 5) yields an estimated minimum southward passage of 28,000 Veerys across the 300 km line of recording stations. Expanding the technique to the whole season yields a 1993 estimated minimum detected passage of 175,000 Veerys across the 300 km transect, based on season totals detected at stations across New York State from 1991-1994.

Discussion

Every technique for monitoring avian populations is subject to limitations and biases involving detectability of

birds, amount of area covered, observer variability, and standardization of analyses (Ralph and Scott 1981; Ralph and others 1993). For example, the number of birds detected by a banding station varies with factors such as number of nets, duration of daily operation, regional geography, and local habitat characteristics. Similarly, the equipment and environmental variables associated with an acoustic monitoring station, and the method for interpreting the number of passing individuals from calling data, affect the number of individuals detected. Although the limitations and biases of acoustic monitoring are still not completely understood, certain aspects of the technique can be controlled carefully, increasing the potential for standardization and largely eliminating observer variability. Overall, we believe that the biases associated with acoustic monitoring at night are not greater than those inherent in diurnal censusing or mist-netting. In fact, the most serious impediments to widespread application of a night-flight call monitoring program are the sheer volume of data that can be collected in a short time, and the number of hours required to analyze these data. Ongoing research is therefore focusing on computerized automation of data collection and analysis, which will greatly reduce both data-processing time and human-induced biases.

Even given the large number of variables and uncertainties, it is clear that this new technique can detect enormous numbers of migrating birds and can provide information not possible to obtain through more conventional methods. The data from the Texas acoustic monitoring station illustrate how the biases of both acoustic monitoring and banding complement one another in giving a more accurate representation of migration through a region. Each technique detected species that the other missed. Notable regarding the acoustic technique is the detection of relatively rare and secretive species like the Black Rail, a species for which we have little population or migration information.

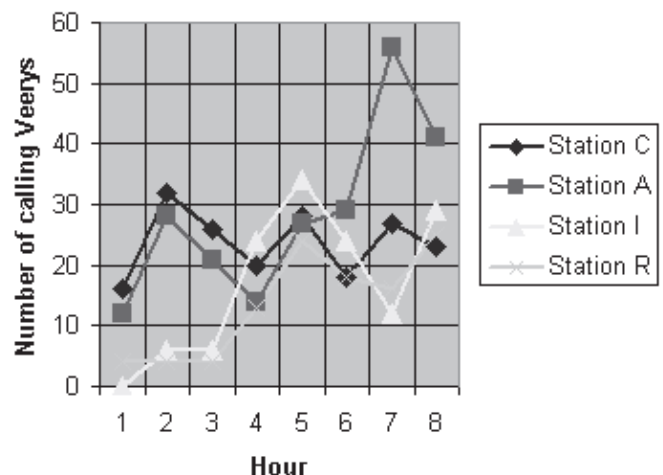


Figure 5—Temporal and geographic comparison of Veery numbers detected by acoustic monitoring at four recording stations in New York State (see fig. 1) during the night of 28-29 August 1993. Recording began at all stations simultaneously at 2030 EDT and continued for 8 hours.

The acoustic stations at Alfred, NY, and Vancouver Island, BC, detected more than an order of magnitude more thrushes than were detected by mist-netting. Furthermore, results from the New York State array reveal that many species migrate in broad geographic fronts with spatially related density gradients. This suggests that acoustically detected numbers aloft may be interpolated between properly spaced inland monitoring stations, resulting in even greater monitoring power.

The MIP counting technique, which theoretically compensates for variable calling rates of birds, is most likely conservative, and additional work toward understanding night-flight calling behavior will likely lead to more sophisticated MIP analysis and higher MIP totals. For example, further work characterizing flight altitudes and average flight speeds of small passerines by radar in different regions and weather conditions should lead to more accurate MIP calculations.

Acoustically determined numbers of migrants with MIP are tallied with certain assumptions. MIP considers that migrants typically progress in some consistent direction, as opposed to circling. Whole-season surveillance radar studies support this assumption (e.g., Graber 1968), but certain weather conditions, especially combined with the presence of artificial lighting, can cause circling. The possibility of circling birds must be evaluated before applying MIP.

A second assumption is that the apparent broad front density of migration of certain species, for example Veery, allows interpolation between recording stations. Further studies are needed to understand the validity of such interpolation, and to determine the appropriate interstation distances within a transect.

A final assumption is that an acoustic station can census calling species consistently through time, despite inevitable variations in flight altitude, wind conditions, migration routes, and calling behavior. Although this assumption is difficult to prove, one of the strongest pieces of evidence lies in the empirical results from the New York State monitoring stations. These data indicate consistent season totals and migration timing for species amid the variables of multiple seasons (e.g., Gray-cheeked Thrush data in this paper).

Results from several of the pilot studies demonstrate the importance of weather and geographic factors in affecting the monitoring potential at different sites, and suggest that some sites may be better than others for acoustic monitoring at particular seasons. For example, the station in British Columbia detected few calls in spring but heavy calling in fall, while concurrent surveillance radar studies indicated heavy migration over the recording station during both seasons. However, radar studies also indicated that birds were flying higher in spring, above the range of the recording equipment (R. Millikin, personal communication). In spring, birds must cross the 30 km wide Juan de Fuca Strait before flying over the recording station on southern Vancouver Island. In fall, migrant landbirds funnel southward down Vancouver Island. Birds may fly at higher altitudes in spring migration across the Juan de Fuca Strait than they do in their fall flight down Vancouver Island. Further research on microphone designs will define the altitudes at which migrants can be acoustically censused, but a site like the southern end of Vancouver Island generally appears not to be a good location to acoustically study migration during spring.

As a second example of the effects of weather, the acoustic station on Florida's east coast detected large flights only under specific wind directions in spring. On east to south-east winds only light calling was detected, whereas large flights predictably occurred when winds were from south to west, tending to "wind-drift" migrants against the coast. Under these latter conditions, the birds apparently prefer to fly at low altitudes and to hug the coastline during their northbound flight, instead of flying out over the Atlantic Ocean. Although these weather and geographic variables may appear as serious limitations of the acoustic monitoring technique, we believe that knowledge of such variation can be used to select sites that maximize the consistent monitoring of large numbers of migrants.

In the New York State array, relatively consistent acoustic patterns have been revealed for the 1991-1994 fall migrations, amid a wide range of seasonal weather variables (see also Evans and Mellinger 1999). One advantage of an inland, east-west running transect of recording stations is that it can account for variations in the flow of migrants due to variable seasonal weather conditions. In one season, some migrants may pass over the east side of a recording-station transect; in another year these migrants might pass over the western side. Therefore, an east-west running transect of stations may act as a "recording net," able to more consistently monitor the flow of migration amid seasonal weather variations than a single station can.

The question most frequently asked regarding this emerging technique involves species identification and problems associated with non-calling or non-detected individuals. We believe that the issue of species identification has been addressed partly through careful comparisons with calling birds of known identity, and through the use of modern spectrographic analysis. Our knowledge of call identities and variations within species will be refined as field recordists continue to work in new areas of North America, and as computer-analysis techniques become more sophisticated. In the short term, inclusion of a call-type in a complex of similar species does not preclude our ability to monitor these species at certain geographic localities or times of year. For example, some calls in figure 3 are placed in the species complex #5, which includes at least eight species. However, considering extensive diurnal migration observations made along the east coast of Florida during early May (Cruickshank and Taylor databases), the likely callers are Blackpoll Warbler and to a lesser extent, Connecticut Warbler. Similarly, all the calls placed in species complex #4 (fig. 3) are most likely from Northern Parula because other species in this complex are not known to be regular migrants at this time of year in eastern Florida.

The problem of noncalling or "missed" birds is potentially more troubling, but may be resolved through innovative comparisons with radar data (Gauthreaux, personal communication). As with other monitoring techniques, we seek a consistent index of species abundance. Therefore, even if we cannot reliably estimate the probability that a given bird calls while passing over a recording station, acoustic monitoring still will be useful if the number of birds detected is positively correlated with the number of birds aloft. However, comparisons and calibrations with other techniques are complicated by the presence of individuals

of abundant, non-vocal species. For example, on nights when large numbers of Gray Catbirds (*Dumatella carolinensis*) and Red-eyed Vireos (*Vireo olivaceus*) are migrating, close correspondence between acoustic and radar data might not be expected, because neither species is known to give night-flight calls.

Another barrier to widespread use of the night-flight call monitoring technique is the large amount of data analysis involved. Thousands of calls may occur over a monitoring site in a single evening, and hundreds of hours of tape may be generated in even a limited study. One of the great potentials of the acoustic-monitoring technique is now being developed—the use of signal processing technology to automatically extract and classify calling information from recorded tapes. Recent work toward this goal has been carried out by the Cornell Laboratory of Ornithology's Bioacoustics Research Program (Mellinger and Clark 1993; Fristrup and Watkins 1994; Mills 1995; Taylor 1995). Automated detection of call notes and classification into species or complexes of species will make large-scale analysis of flight-call data possible.

In conclusion, we believe that acoustically monitoring night-flight calls of migrating birds offers enormous potential for improving understanding of migration routes, migration timing, and species composition at specific sites. Ultimately, we believe the technique will help us to monitor population changes of certain migratory species. Careful selection of recording sites can minimize the effects of geography or local weather, and inland transects of recording stations can lead to consistent monitoring. Acoustic monitoring is promising for its ability to detect species that are difficult to study by other means; for example, the migration of secretive grassland birds (Evans and Mellinger 1999), the passage of boreal-nesting species such as Gray-cheeked Thrush (Blanchard and Droege 1993) or the movements of special-concern species such as Bicknell's Thrush (Evans 1994). This new methodology will be especially valuable when used in conjunction with other, more conventional techniques, such as mist-netting and diurnal counts. The information that can be derived from acoustic monitoring is qualitatively different, however, from that obtained by other methods.

As humans, our ability to study the species-specific movements of nocturnal migrants always has been dependent on

what we encounter on the ground, during the day. As such, we traditionally may have missed the bulk of the true migration, which passes undetected overhead. The emerging techniques we describe here, especially if combined with exciting new avian detection capabilities of Nexrad radar (Larkin 1991; Gauthreaux 1996), will open a wide window into one of the great mysteries of nature.

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